Progress Report

Joint Industry Project on Design of Cathodic Protection Retrofits for Offshore Structures

submitted by

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Task I: Protocol for Maintenance Current Density Determination

Background. The objective of this task is to perform experiments and analyses from which a protocol(s) for field determination of maintenance current density on offshore structures that are candidates for cp retrofit can be proposed. An important experimental component of accomplishing this is to evaluate the various techniques that have been identified for determining current demand of the structure (alternately, anode current output). Techniques that were considered appropriate for further study include 1) Potential Difference - Modified Dwight Equation (Slope Parameter) Method, 2) Swain Meter Measurements, 3) Field Gradient Measurements, and 4) Anode Potential Measurements. No specific experiments are planned regarding 4), but it is intended that potential data that are acquired during the course of the other experiments be evaluated within the context that anodes may polarize in the low current density regime such that a potential - current density trend is apparent.

Potential Difference - Modified Dwight Equation Method. This approach is based upon the slope parameter equation,

$$\phi_c = (R_t \cdot A_c)i_c + \phi_a,$$

where

ϕ_c and ϕ_a are the cathode and anode potentials, respectively,
R_t is the total circuit resistance,
A_c is cathode area, and
i_c is cathode current density.

Thus, if the two potentials, cathode area, and resistance are known, then i_c can be calculated. The approach proposes that this information can either be acquired from surveys or calculated from survey data. Such information has now been made available for several Chevron and Shell structures which were surveyed by Deepwater according to their Polarscan method. However, a review of these has indicated that critical information is either missing or the values are unrealistic such that the parameters identified above cannot be determined. Foremost of these is reliable anode dimensions from which R_a (anode resistance) and, hence, R_t, can be determined. Dan Townley has recently extended an invitation for us to provide input to a survey to be performed this summer of one of the structures that is represented in the above Polarscan database. We have responded to this by giving Dan input which intends to estimate dimensions from a video image of a fouled anodes and its standoffs. Other aspects of our input to this survey are discussed below.

Swain Meter and Field Gradient Experiments. Activities in these categories have been based three prototype In activated aluminum anodes that were deployed at NRLKW in early March, 1997. Data from these have been acquired during three visits to Key West with relevant aspects of these being presented below. Each of the three anodes was individually mounted upon a pair of bare steel plates, as illustrated in Figure 1. The electrical circuitry was such that each anode was connected to an uncoated steel sea wall through a current controlling resistor (present for two of the anodes but not the third) such that target current outputs were 4.5, 2 and 1 A, respectively. The anodes were deployed in about 2.5 m deep sea water. Also included in the electrical wiring was a pair of 0.01 Ω resistors, one in series with each standoff, such that net current output of each anode could be measured. Figure 2 provides a schematic illustration of this circuit.

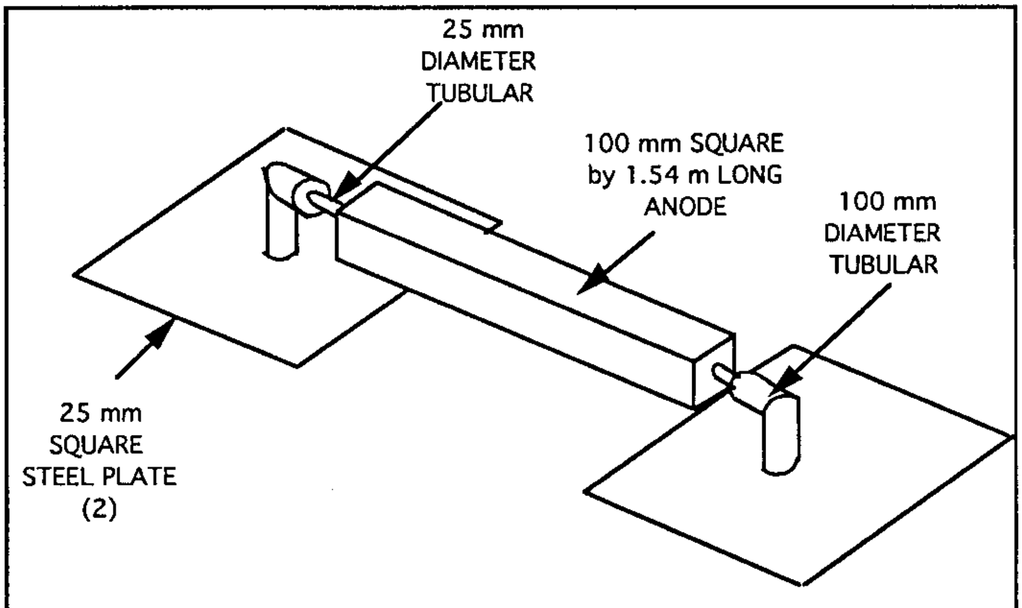

Figure 1: Schematic illustration of anode set-up.

Measurement Procedures. Anode current outputs were measured according to each of the three techniques:

1. Voltage drop across 0.01 Ω resistors,
2. Swain meter, and
3. Two electrode potential drop.

The first of these, voltage drop across 0.01 Ω resistors, is first principles based and corresponds to general corrosion current measurement practice.

The Swain meter, on the other hand, employs a non-contact sensor and meter which is based upon the principle that a direct current induces a

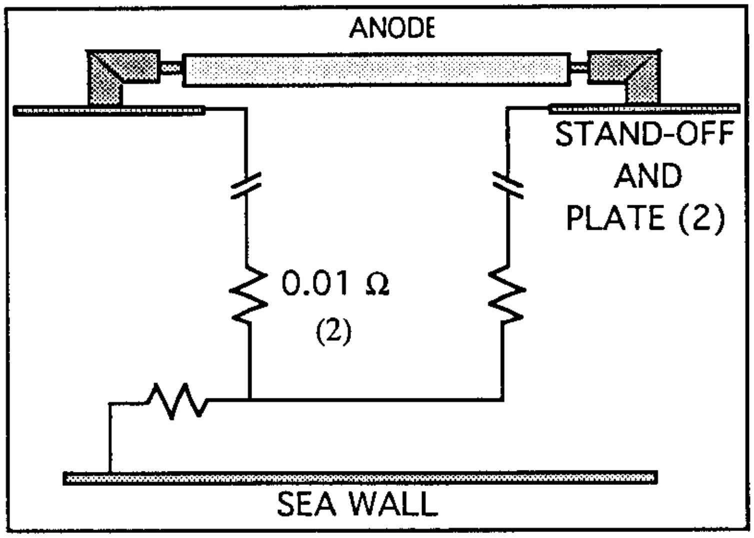

Figure 2: Electrical circuitry for anode test arrangement.

magnetic field in its vicinity, the magnitude of which is proportional to the current. By clipping the sensing element sequentially about each of the two stand-offs of a given anode, the net current passing through the metallic path and, hence, the anode current output is determined. Apparent shortcomings of this method are that the sensing element does not discriminate between 1) the metallic path current, 2) current in the sea water near the element, and 3) magnetic field effects either in the water or steel other than result from the cp current. It has been projected that residual magnetism in the steel has been a historical source of error; and this along with other uncertainty has prompted concerns regarding accuracy. A new version of this meter, designated as the MER (magnetic error resistive), which is the unit that is being used for the present measurements, is advertised as reducing this latter error by a factor of two or three.

The procedure employed for the Swain meter measurements involves taking reading pairs (one reading with the sensor about the current conducting element in one orientation and a second with the sensor reversed (in the 180° orientation)) and then averaging the absolute value of these (one reading is negative and the other positive) to yield a single datum. This was repeated at each of the following five locations:

1. About the lead wire where this connects to the plate upon which the anode is attached,
2. About the stand-off where this is welded to the plate,
3. At the mid-height of the stand-off,
4. At the stand-off 90° weld, and
5. About the core immediate to the anode.

Each of these locations is identified in Figure 3. Factors considered in making measurements at multiple locations were, first, the need to develop information regarding how component geometry or geometry differences might affect readings and, second, the fact that the plate and standoff pair, in addition to the sea wall, are receiving current, the magnitude of which is not

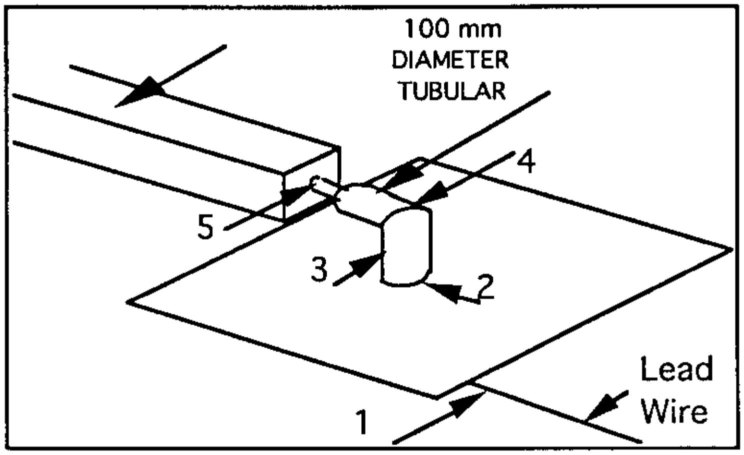

Figure 3: Locations on anode system for Swain meter measurements.

included in data acquired from voltage measurement across the 0.01 Ω resistors.

During the second data acquisition at NRLKW anode current output determination according to the two electrode potential difference was based upon a three electrode (Ag/AgCl) stand-off device that was made available by NRLKW, as illustrated in Figure 4. Because of subsequent concerns that the size of this might alter the potential field, an alternative electrode holding device was constructed and employed on the next visit. This is illustrated in Figure 5.

Results and Discussion. Table 1 presents the results of shunt and Swain meter measurements during the second visit (April, 1997) and Table 2 shows this same information for the third (May, 1997). These data indicate that, first, the scatter between the different measurements sites (Figure 3) was small and within the experimental error and, second, the currents measured with the Swain meter were in excellent agreement with those calculated from the voltage drop across the shunts. It is concluded based upon these results that the Swain meter provided an accurate determination of anode current output for the present experimental arrangement.

It is understood that a deterrent to using the Swain meter for measurements upon actual structures is that the fouling buildup upon standoffs must first be removed, which is obviously an expensive operation. With this in mind, arrangements have been made to lease a 30.5 cm (12.0 inch) diameter clip from the Swain Company for one month with an option to buy at no additional cost. The intention is to evaluate this using the anodes deployed at NRLKW and determine how error, resolution, and scatter are affected compared to the present clip (12.7 cm (5.0 in) diameter). The protocol submitted to Dan Townley for incorporation into the cp survey of a Chevron structure this summer includes Swain meter measurements; however, it is unclear at present it these will be included.

Table 3 presents results from the field gradient measurements using the device in Figure 4 (data acquired April 20, 1997). These reveal that, while the data were mutually self consistent and reproducible, current calculated from

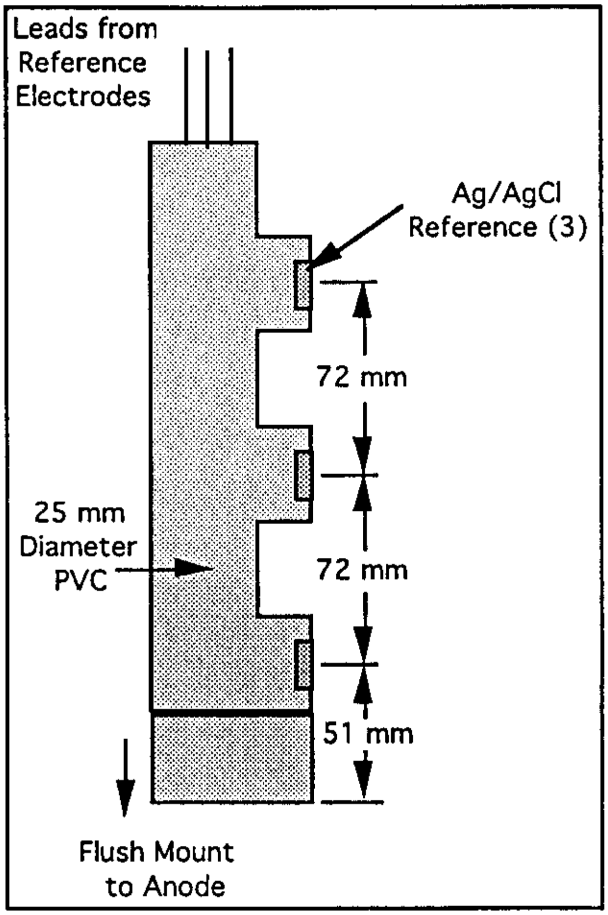

Figure 4: Schematic drawing of field gradient measuring device.

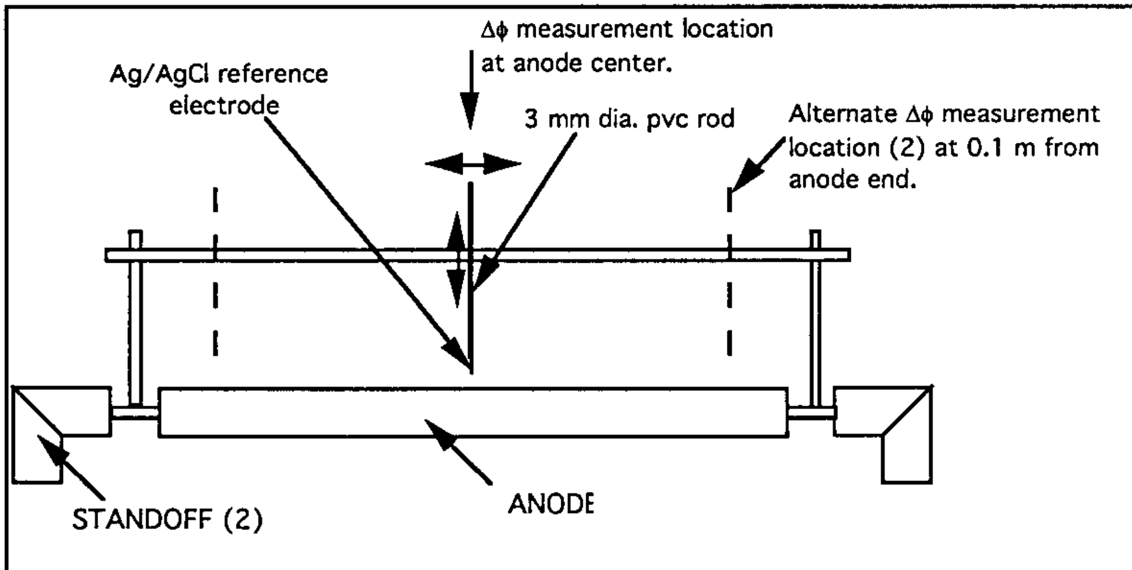

Figure 5: Alternate arrangement for field gradient measurements.

Table 1: Anode output data from shunts and Swain meter (April 20, 1997).

ANODE	V (SHUNT), mv		I, A (Shunt)			CURRENT, A (Swain Meter)							
NUMBER	Left	Right	L	R	Total		Left			Right			Total
							Pos.	Neg.	Avg.	Pos.	Neg.	Avg.	
						Site 1	2.30	2.25	2.28	2.23	2.25	2.24	4.52
						Site 2	2.28	2.20	2.24	2.16	2.17	2.17	4.41
1	21.86	22.62	2.19	2.26	4.45	Site 3	2.35	2.40	2.38	2.25	2.27	2.26	4.64
						Site 4	-	-	-	2.37	2.34	2.36	
						Site 5	2.23	2.27	2.25	2.14	2.09	2.12	4.37
						Avg.							4.49
						Site 1	0.91	0.97	0.94	0.97	1.00	0.99	1.93
						Site 2	1.10	1.09	1.10	1.18	0.96	1.07	2.17
2	10.4	11.6	1.04	1.16	2.20	Site 3	1.12	1.02	1.07	1.15	1.15	1.15	2.22
						Site 4	1.11	0.86	0.99	1.07	0.78	1.93	1.92
						Site 5	1.00	0.99	1.00	1.14	1.03	1.14	2.14
						Avg.							2.08
						Site 1	0.43	0.41	0.42	0.46	0.45	0.46	0.88
						Site 2	0.43	0.55	0.49	0.38	0.43	0.41	0.90
3	4.35	4.34	0.44	0.43	0.87	Site 3	0.43	0.39	0.41	0.46	0.44	0.45	0.86
						Site 4	0.48	0.42	0.45	0.50	0.51	0.50	0.95
						Site 5	0.43	0.41	0.42	0.48	0.46	0.47	0.89
						Avg.							0.90

these were about 60 percent below those measured via either the Swain meter or the shunts. Correspondingly. Table 4 shows this same information as was subsequently acquired based upon the instrumentation setup shown in Figure 5. In this case the currents calculated from the potential field data are about included in data acquired from voltage measurement across the 0.01 Ω resistors. electrode holder (Figure 4) was not responsible for this difference. Also, since the field gradient procedure is first principles based and not empirical, the systematic difference between the results obtained according to this procedure compared to the other techniques must be attributed to 1) some aspect of the procedure being inappropriate, 2) measurement error, or 3) a problem with the calculation (or to some combination of these). These alternatives are being studied. However, a preliminary assessment is that this technique may not be adequately reliable for the intended use.

Table 2: Anode output data from shunts and Swain meter (May 23, 1997).

ANODE NUMBER	V (SHUNT), mv		I, A (Shunt)			CURRENT, A (Swain Meter)							
	L	R	L	R	Total		Left			Right			Total
							Pos.	Neg.	Avg.	Pos.	Neg.	Avg.	
1	22.57	23.49	2.26	2.35	4.61	Site 1	2.39	2.37	2.38	2.29	2.25	2.27	4.65
						Site 2	2.40	2.41	2.41	2.20	2.30	2.25	4.66
						Site 3	2.29	2.40	2.36	2.26	2.21	2.24	4.60
						Site 4	-	-	-	-	-	-	-
						Site 5	2.40	2.31	2.36	2.26	2.21	2.34	4.70
						Avg.							4.65
3	4.6	4.77	0.46	0.48	0.94	Site 1	0.44	0.45	0.45	0.46	0.45	0.46	0.91
						Site 2	0.36	0.51	0.46	0.36	0.40	0.38	0.84
						Site 3	0.43	0.43	0.43	0.36	0.40	0.38	0.81
						Site 4	-	-	-	-	-	-	-
						Site 5	0.40	0.39	0.40	0.43	0.42	0.43	0.83
						Avg.							0.85

Note: Anode 2 was found to be disconnected at the time of this visit, and so no data were recorded.

Table 3: Results from potential field measurements, (April, 1997).

ANODE NUMBER	LOCATION NUMBER	REF. ELECT. NO.	EFFECT. RAD., cm	POT., v. (AgAgCl)	POT. DIFF, Ohm's (1-2)	R., Ohms D's Eqn.	R. DIFF, Ohms	I, A
		1	10.16	-0.988	0.028	0.0641	0.0110	2.55
	1	2	17.35	-0.960		0.0531		
		3	-	-0.937				
		4 *	-	-1.031				
		1	10.16	-0.995	0.029	0.0641	0.0110	2.63
1	2	2	17.35	-0.966		0.0531		
		3	-	-0.994				
		4 *	-	-1.047				
		1	10.16	-0.986	0.027	0.0641	0.0110	2.45
	3	2	17.35	-0.959		0.0531		
		3		-0.936				
		4 *		-1.037				
							Avg.	2.54
		1	10.16	-1.037	0.015	0.0641	0.0110	1.36
	1	2	17.35	-1.022		0.0531		
		3	-	-1.01				
		1	10.16	-1.043	0.017	0.0641	0.0110	1.55
2	2	2	17.35	-1.026		0.0531		
		3	-	-1.015				
		1	10.16	-1.036	0.012	0.0641	0.0110	1.09
	3	2	17.35	-1.024		0.0531		
		3		-1.013				
							Avg.	1.33
		1	10.16	-1.064	0.008	0.0641	0.0110	0.73
	1	2	17.35	-1.056		0.0531		
		3	-	-1.052				
		1	10.16	-1.063	0.006	0.0641	0.0110	0.55
3	2	2	17.35	-1.057		0.0531		
		3	-	-1.052				
		1	10.16	-1.060	0.005	0.0641	0.0110	0.45
	3	2	17.35	-1.055		0.0531		
		3		-1.052				
							Avg.	0.58

Table 4: Results from potential field measurements, (May, 1997).

ANODE NUMBER	LOCATION NUMBER	REF. ELECT. NO.	EFFECT. RAD., cm	POT., v. (Ag/AgCl)	POT. DIFF, Ohm's (1-2)	R., Ohms D's Eqn.	R. DIFF, Ohms	I, A
1	1	1	10.16	-1.009	0.024	0.0641	0.0084	2.82
		2	15.24	-0.985		0.0557		
	2	1	10.16	-1.013	0.024	0.0641	0.0084	2.93
		2	15.24	-0.989		0.0557		
	3	1	10.16	-1.000	0.014	0.0641	0.0084	1.64
		2	15.24	-0.986		0.0557		
							Avg.	2.46
2	1	1	10.16	-1.056	0.009	0.0641	0.0084	1.14
		2	15.24	-1.047		0.0557		
	2	1	10.16	-1.062	0.030	0.0641	0.0084	1.37
		2	15.24	-1.020		0.0557		
	3	1	10.16	-1.066	0.022	0.0641	0.0084	1.12
		2	15.24	-1.034		0.0557		
							Avg.	1.21
3	1	1	10.16	-1.090	0.009	0.0641	0.0084	1.02
		2	15.24	-1.081		0.0557		
	2	1	10.16	-1.090	0.000	0.0641	0.0084	0.00
		2	15.24	-1.090		0.0557		
	3	1	10.16	-1.083	0.003	0.0641	0.0084	0.35
		2	15.24	-1.080		0.0557		
							Avg.	0.46

Task II: Retrofit Cathodic Protection Design for Depolarized Structures

Background. The objective of this task is to perform experiments and analyses to identify how, if at all, the cp current density requirements for a depolarized or partially depolarized structure differ from those of a structure that is still polarized. The test plan for accomplishing this is shown in Table 5. This is based upon the following sequential steps: 1) cathodically polarizing a series of specimens such that a polarized steady-state typical of long-term Gulf of Mexico performance is attained, 2) affecting various degrees of depolarization, 3) repolarizing to simulate application of a retrofit cp system, and 4) determining the current density demand associated with 3). To this end, 24 nominally 100 mm diameter by 150 mm long carbon steel pipe sections have been arranged in a 0.03 m/sec (0.10 ft/sec) sea water flow loop where each specimen is connected through a 6.5 Ohm resistor (resistance-cathode area product 0.32 $\Omega \cdot m^2$) to an aluminum anode. These experiments have now been underway for almost three months.

Results. Figures 6 and 7 show typical potential and current density versus time plots. In all cases the specimens polarized to what appears to be steady-state values in a relatively brief period. Here, potential is approximately -1.00 v (Ag/AgCl) and current density for the specimens ranges from 35 to 73 mA/m^2. A concern arises from the fact that these values are above what is anticipated to be the case for older Gulf of Mexico structures. For example, Kennelley and Mateer reported current density demand for the two structures they investigated as 3.4 and 8.8 mA/m^2 after some 20 years. Al Goolsby has indicated that their instrumented anodes on Bullwinkle at -37 m revealed current density demand after one year to be about 18 mA/m^2. Also, this current density had dropped by about a factor of three between day 55 and one year (please treat this information as confidential as permission to release has not yet been granted). Clearly, it is desired that we get to the 10-20 mA/m^2 range before beginning the depolarization phase of these experiments. In an effort to affect a current density reduction, the flow rate on one of the branches of the

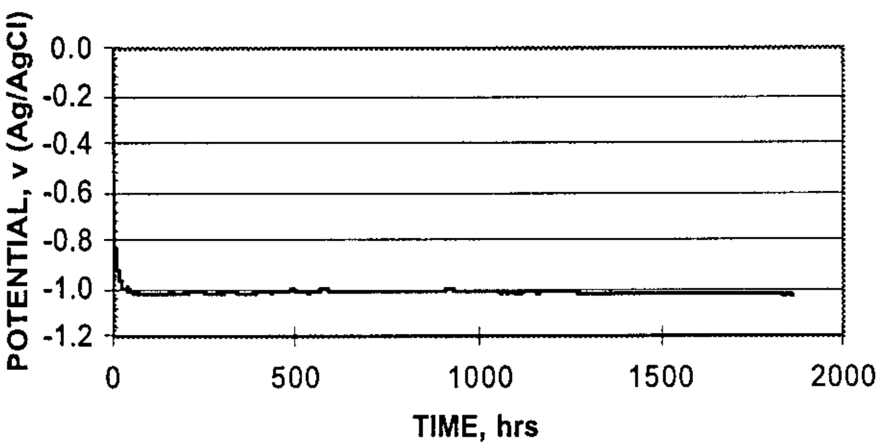

Figure 6: Potential versus exposure time for specimen no. 22.

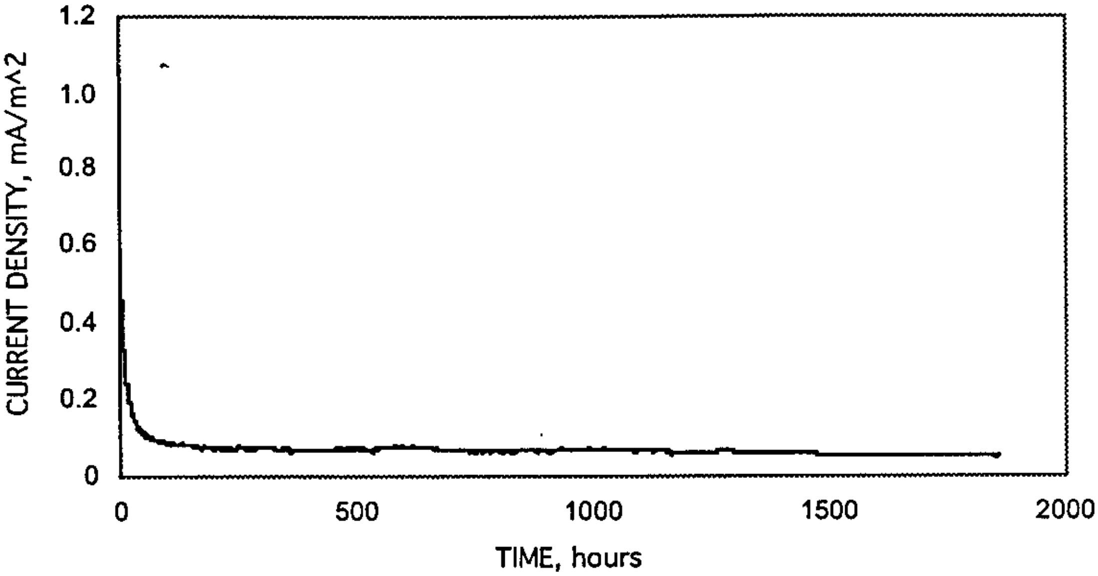

Figure 7: Current density versus time for specimen no. 22.

test loop (four specimens) was reduced two weeks ago from 0.03 to about 0.02 m/s. Prior to this the average current density for these specimens was 50 mA/m^2 and one week after the reduction 44 mA/m^2. It is doubtful that the needed current density decrease can be accomplished by this means. It is certainly possible that the current densities on the present specimens will continue to decrease with time; however, the data do not show that this is taking place. We are in a position to wait several months, but beyond this the timing of the project would be adversely affected. Figure 8 shows data that has

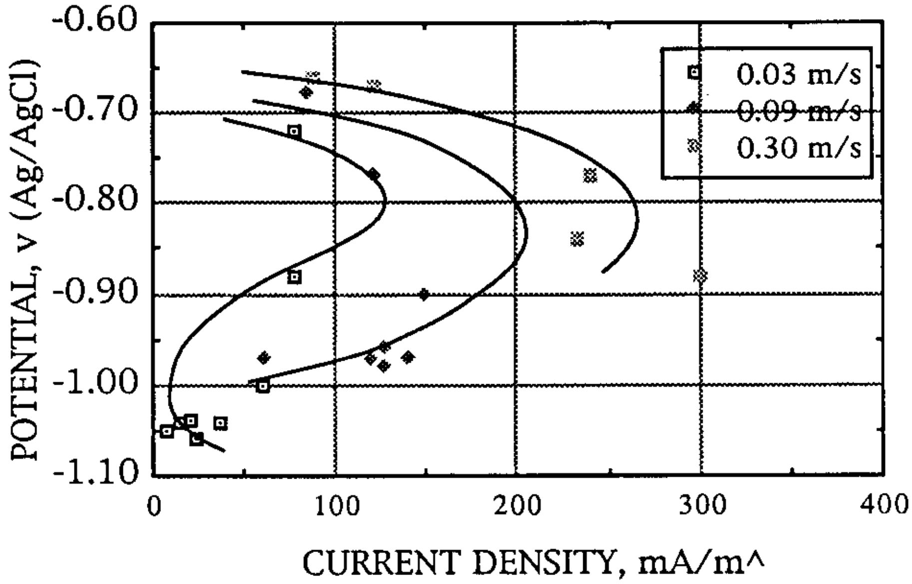

Figure 9: Steady-state potential versus current density trend for steel specimens polarized galvanically in sea water at flow rates of 0.03, 0.09, and 0.30 m/s.

evolved from the companion Sea Grant sponsored project where the velocity dependence of cathodic protection is sea water has been investigated using a test system similar to that for the present tests. In this case, the averagecurrent density for specimens whose long-term potential was in the range -0.90 to -0.95 v was 121 mA/m^2, whereas for those near -1.05 v this value was 20 mA/m^2. A viable option is then to temporarily decrease the slope parameter and determine if these same potentials and current densities can be achieved. It is recommended that, if the requisite reduction does not occur in the next month, the resistance be increased.

Task III: Cathodic Protection Retrofit Timetable for Aged Structures Which Are Still Polarized

Background. There is evidence that anodes on at least some aged structures operate at current densities below what has been historically envisioned (see above). At the same time, it is known that current capacity decreases with decreasing current density, as shown, for example, in Figure 9. For the two

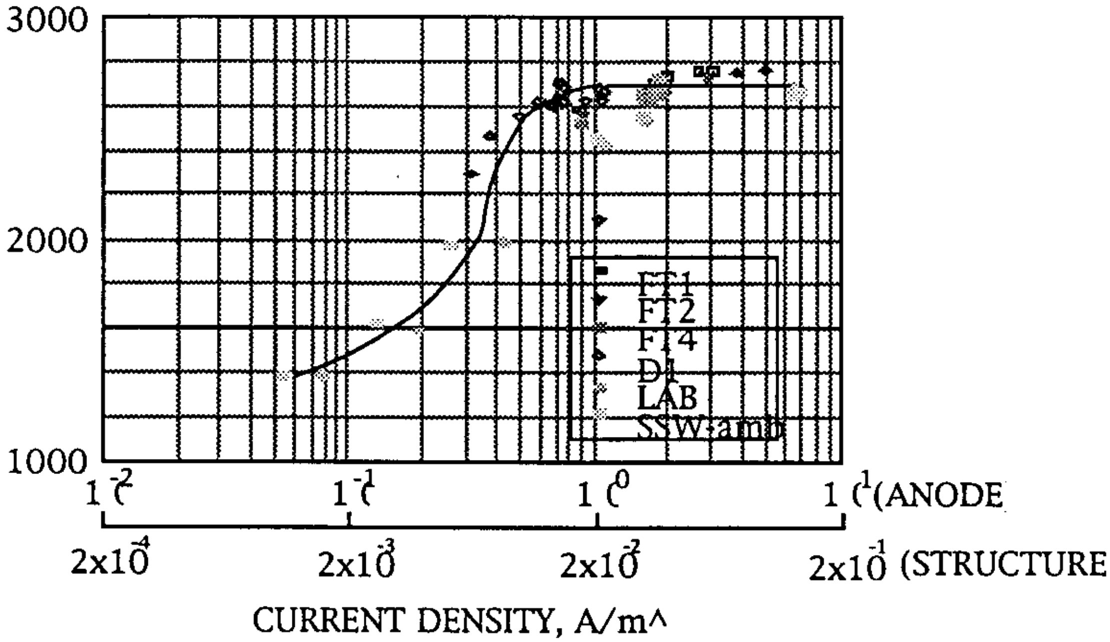

Figure 9: Current capacity for aluminum anodes as a function of current density.

structures studied by Kennelley and Mateer the anode current densities prior to retrofit were 0.50 and 0.93 A/m^2. From the above plot this translates to current capacities of about 2,090 and 2,370 A-h/kg (950 and 1,080 A-h/lb), respectively, or reductions of about 21 and 10 percent compared to typically assumed design values. Of concern also is the strong dependence of current capacity upon current density in the current density range near 0.4 mA/m^2. At the same time, little historical attention has been directed toward the low current density regime of the current capacity versus current density relationship. Accordingly, the objective of this task is to experimentally determine anode current capacity 1) at relatively low current densities and 2) for current density histories that are anticipated to occur upon aged structures.

Test Plan and Progress. The test plan involves current capacity determinations upon several Hg and In activated aluminum anodes in association with current density histories which simulate the life of actual galvanic cp systems. Details of the experiments were presented in the revised Work Plan (see January 8, 1997 Progress Report). Progress to-date has been delayed because of a personnel problem; however, this have since been resolved; and the long-term timetable of the project should not be effected. Accomplishments include the following:

1. Acquisition of anode test materials. Ingots representing two heats of In activated anode and one heat of a Hg activated anode have been acquired to-date. A listing of these is provided in Table 6. Three other heats of the latter material were also acquired, but the compositions for these were out of specification. Efforts are underway to acquire several more samples of each anode type.

Table 6: Composition of anodes received to-date.

ANODE DESIGNATION	ANALYSIS NUMBER	COMPOSITION, w/o						
		Zn	In	Hg	Si	Cu	Fe	Cd
1	1	5.61	0.028	-	0.033	0.001	0.046	<0.002
	2	5.72	0.028	-	0.032	9E-04	0.046	<.002
2	1	4.41	0.013	-	0.087	0.002	0.038	0.001
	2	5.11	0.016	-	0.092	0.002	0.053	0.001
	3	5.62	0.017	-	0.092	0.002	0.039	0.001
3	1	1.46	-	0.038	0.05	2E-04	0.058	0.001
	2	1.56	-	0.044	0.052	6E-04	0.059	0.001
	3	0.39	-	0.043	0.04	0.002	0.047	0.001

2. Arrangements are being made with a local company whereby we should be able to compositionally analyze individual samples for a reasonable price

3. The experimental setup for performing the current capacity tests is near completion and qualification tests are underway.